

Hadron production experiments

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Abstract

The HARP and NA61/SHINE hadroproduction experiments as well as their implications for neutrino physics are discussed. HARP measurements have already been used for predictions of neutrino beams in K2K and Mini-BooNE/SciBooNE experiments and are also being used to improve the atmospheric neutrino flux predictions and to help in the optimization of neutrino factory and super-beam designs. First measurements released recently by the NA61/SHINE experiment are of significant importance for a precise prediction of the J-PARC neutrino beam used for the T2K experiment. Both HARP and NA61/SHINE experiments provide also a large amount of input for validation and tuning of hadron production models in Monte-Carlo generators.

Keywords: hadron production measurements, accelerator neutrino beams, atmospheric neutrino fluxes, hadron production models

1. The HARP experiment

The HARP experiment [1] at the CERN PS was designed to make measurements of hadron yields from a large range of nuclear targets from hydrogen to lead and for incident particle momenta from 1.5 to 15 GeV/c. The main motivations are the measurement of pion yields for a quantitative design of the proton driver of a future neutrino factory and a super-beam [2], a substantial improvement in the calculation of the atmospheric neutrino flux [3] and the measurement of particle yields as input for the flux calculation in accelerator neutrino experiments [4], such as K2K [5, 6], MiniBooNE [7] and SciBooNE [8]. In addition to these specific aims, the data provided by HARP are valuable for validation and tuning of hadron production models used in simulation programs. The HARP experiment is described in more detail below in order to illustrate some common features of modern hadron production experiments.

To provide a large angular and momentum coverage of the produced charged particles the HARP experiment makes use of a large-acceptance spectrometer consisting of forward and large-angle detection systems. A detailed description of the experimental apparatus can be

found in Ref. [1]. The forward spectrometer — based on large area drift chambers [9] and a dipole magnet complemented by a set of detectors for particle identification (PID): a time-of-flight wall [10] (TOFW), a large Cherenkov detector (CHE) and an electromagnetic calorimeter — covers polar angles up to 250 mrad which is well matched to the angular range of interest for the measurement of hadron production to calculate the properties of conventional neutrino beams. The large-angle spectrometer — based on a Time Projection Chamber (TPC) located inside a solenoidal magnet — has a large acceptance in the momentum and angular range for the pions relevant to the production of the muons in a neutrino factory. It covers the large majority of the pions accepted in the focusing system of a typical design. The neutrino beam of a neutrino factory originates from the decay of muons which are in turn the decay products of pions.

A full set of data collected by the HARP experiment with solid thin (5% of nuclear interaction length, λ_I) and cryogenic targets have been analyzed and published [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Those results cover all the physics subjects discussed above.

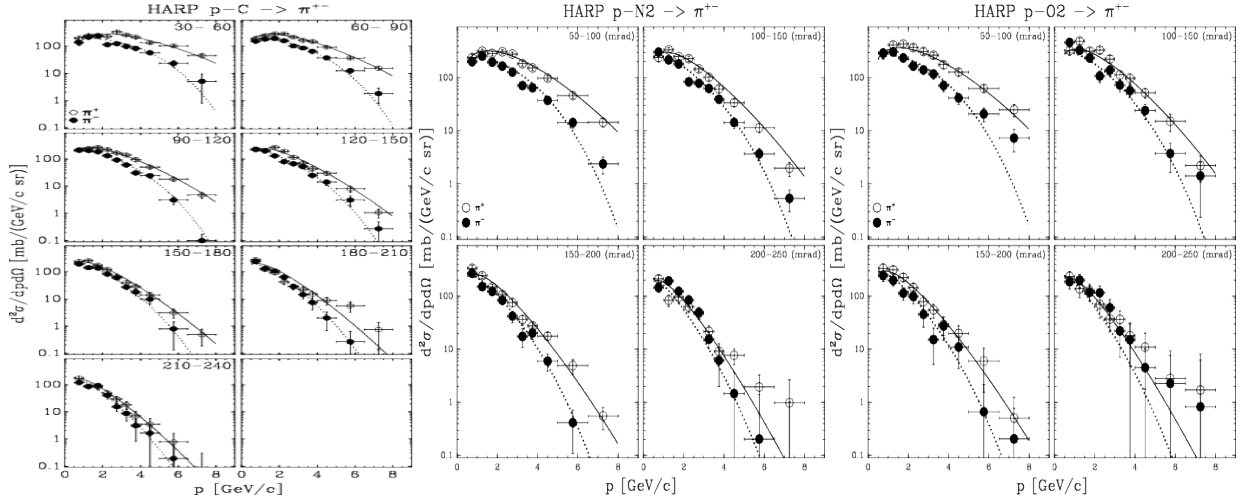


Figure 1: Measurements of the double-differential production cross-sections of π^+ (open circles) and π^- (closed circles) from 12 GeV/c protons on carbon (left), N_2 (middle) and O_2 (right) targets as a function of pion momentum, p , in bins of pion polar angle, θ , in the laboratory frame. Different panels show different angular intervals. The error bars shown include statistical errors and all (diagonal) systematic errors. The curves show the SW parametrization of Eq. (3) with parameters given in Ref. [14] (solid line for π^+ and dashed line for π^-).

1.1. Results obtained with the HARP forward spectrometer

A detailed description of established experimental techniques for the data analysis in the HARP forward spectrometer can be found in Refs. [11, 12, 13, 14]. Only a brief summary is given here.

The absolutely normalized double-differential cross-section for a process like $p + \text{Target} \rightarrow \pi^+ + X$ can be expressed in bins of pion kinematic variables in the laboratory frame (momentum, p_π , and polar angle, θ_π), as

$$\frac{d^2\sigma^{\pi^+}}{dp d\Omega}(p_\pi, \theta_\pi) = \frac{A}{N_{A\rho t}} \cdot \frac{1}{\Delta p \Delta \Omega} \cdot \frac{1}{N_{\text{pot}}} \cdot N^{\pi^+}(p_\pi, \theta_\pi), \quad (1)$$

where $\frac{d^2\sigma^{\pi^+}}{dp d\Omega}$ is the cross-section in $\text{cm}^2/(\text{GeV}/c)/\text{srad}$ for each (p_π, θ_π) bin covered in the analysis; $\frac{A}{N_{A\rho t}}$ is the reciprocal of the number density of target nuclei; t is the thickness of the target along the beam direction; Δp and $\Delta \Omega$ are the bin sizes in momentum and solid angle ($\Delta p = p_{\text{max}} - p_{\text{min}}$; $\Delta \Omega = 2\pi(\cos(\theta_{\text{min}}) - \cos(\theta_{\text{max}}))$); N_{pot} is the number of protons on target after event selection cuts; $N^{\pi^+}(p_\pi, \theta_\pi)$ is the yield of positive pions in bins of true momentum and angle in the laboratory frame. Eq. (1) can be generalized to give the inclusive cross-section for a particle of type α

$$\frac{d^2\sigma^\alpha}{dp d\Omega}(p, \theta) = \frac{A}{N_{A\rho t}} \cdot \frac{1}{\Delta p \Delta \Omega} \cdot \frac{1}{N_{\text{pot}}} \cdot M_{p\theta\alpha p'\theta'\alpha'}^{-1} \cdot N^{\alpha'}(p', \theta'), \quad (2)$$

where reconstructed quantities are marked with a prime and $M_{p\theta\alpha p'\theta'\alpha'}^{-1}$ is the inverse of a matrix which fully describes the migrations between bins of true and

reconstructed quantities, namely: lab frame momentum, p , lab frame angle, θ , and particle type, α .

There is a background associated with beam protons interacting in materials other than the nuclear target (parts of the detector, air, etc.). These events are subtracted by using data collected without the nuclear target in place after normalization to the same number of protons on target. This procedure is referred to as the ‘empty target subtraction’.

The event selection is performed in the following way: a good event is required to have a single, well reconstructed and identified beam particle impinging on the nuclear target. A downstream trigger in the forward trigger plane (FTP) is also required to record the event, necessitating an additional set of unbiased, pre-scaled triggers for absolute normalization of the cross-section. These pre-scaled triggers (e.g. 1/64) are subject to exactly the same selection criteria for a ‘good’ beam particle as the event triggers allowing the efficiencies of the selection to cancel, thus adding no additional systematic uncertainty to the absolute normalization of the result. Secondary track selection criteria have been optimized to ensure the quality of the momentum reconstruction as well as a clean time-of-flight measurement while maintaining high reconstruction and particle identification efficiencies [12, 13].

The first HARP physics publication [11] reported measurements of the π^+ production cross-section from a thin 5% λ_1 aluminum target at 12.9 GeV/c proton momentum. This corresponds to the energy of the KEK

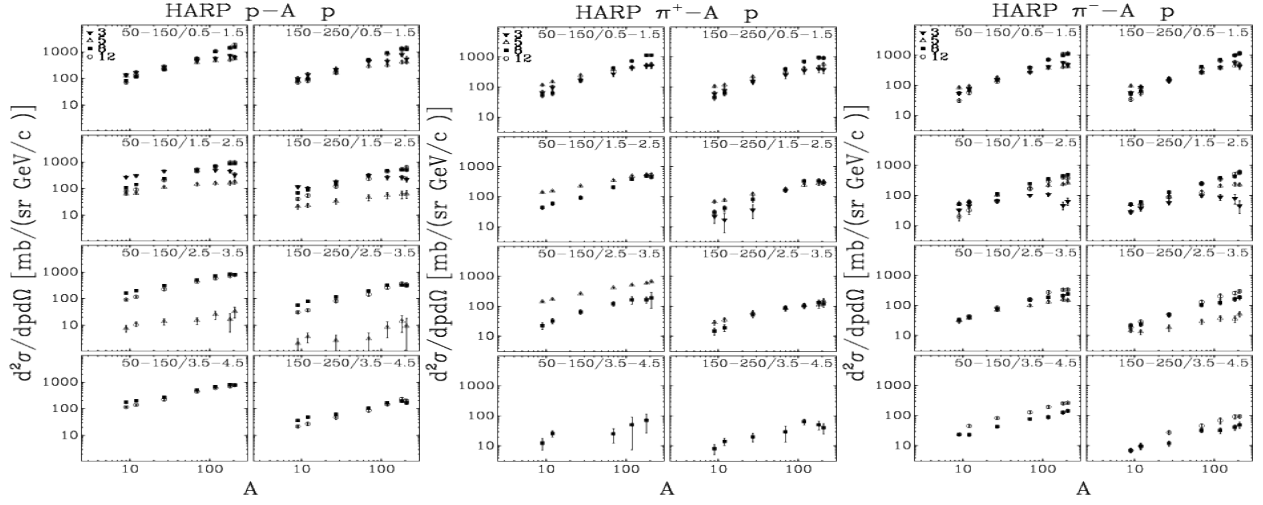


Figure 2: The dependence on the atomic number A of the forward proton production yields in p - A and π^\pm - A ($A = \text{Be, C, Al, Cu, Sn, Ta, Pb}$) interactions averaged over two forward angular regions ($0.05 \text{ rad} \leq \theta < 0.15 \text{ rad}$ and $0.15 \text{ rad} \leq \theta < 0.25 \text{ rad}$) and four momentum regions ($0.5 \text{ GeV}/c \leq p < 1.5 \text{ GeV}/c$, $1.5 \text{ GeV}/c \leq p < 2.5 \text{ GeV}/c$, $2.5 \text{ GeV}/c \leq p < 3.5 \text{ GeV}/c$ and $3.5 \text{ GeV}/c \leq p < 4.5 \text{ GeV}/c$), for the four different incoming beam momenta (3, 5, 8 and 12 GeV/c).

PS and the target material used by the K2K experiment. The results obtained in Ref. [11] were subsequently applied to the final K2K neutrino oscillation analysis [6], allowing a significant reduction of the dominant systematic error associated with the calculation of the so-called far-to-near ratio from 5.1% to 2.9% (see [11] and [6] for a detailed discussion) and thus an increased K2K sensitivity to the oscillation signal.

The next HARP goal was to contribute to the understanding of the MiniBooNE and SciBooNE neutrino fluxes. They are both produced by the Booster Neutrino Beam at Fermilab which originates from protons accelerated to 8.9 GeV/c by the booster before being collided against a beryllium target. A fundamental input for the calculation of the resulting ν_μ flux is the measurement of the π^+ cross-sections from a thin 5% λ_1 beryllium target at exactly 8.9 GeV/c proton momentum.

These double-differential cross-sections were measured in the kinematic range from $0.75 \text{ GeV}/c \leq p_\pi \leq 6.5 \text{ GeV}/c$ and $0.030 \text{ rad} \leq \theta_\pi \leq 0.210 \text{ rad}$, subdivided into 13 momentum and 6 angular bins [13]. A typical total uncertainty of 9.8% on the double-differential cross-section values and a 4.9% uncertainty on the total integrated cross-section are obtained. These HARP results have been used for neutrino flux predictions [24] in the MiniBooNE [25] and SciBooNE experiments [8].

Sanford and Wang [26] have developed an empirical parametrization for describing the production cross-sections of mesons in proton-nucleus interactions (e.g. $p+A \rightarrow \pi^+ + X$). This Sanford-Wang (SW) parametriza-

tion has the functional form:

$$\frac{d^2\sigma}{dpd\Omega}(p, \theta) = \exp[c_1 - c_3 \frac{p^{c_4}}{p_b^{c_5}} - c_6 \theta (p - c_7 p_b \cos^{c_8} \theta)] p^{c_2} (1 - \frac{p}{p_b}), \quad (3)$$

where X denotes any system of other particles in the final state; p_b is the proton beam momentum in GeV/c; p and θ are the π^+ momentum and angle in units of GeV/c and radians, respectively; $d^2\sigma/(dpd\Omega)$ is expressed in units of mb/(GeV/c sr); $d\Omega \equiv 2\pi d(\cos\theta)$; and the parameters c_1, \dots, c_8 are obtained from fits to meson production data. HARP data were fitted using this empirical SW parametrization. This is a useful tool to compare and combine different data sets. A global SW parametrization for forward production of charged pions as an approximation of all the studied datasets is provided in Ref. [22]. It can serve as a tool for quick yields estimates.

The next HARP analysis was devoted to the measurement of the double-differential production cross-section of π^+ in the collision of 12 GeV/c protons (see Fig. 1) and pions with a thin 5% λ_1 carbon target [14]. These measurements are important for a precise calculation of the atmospheric neutrino flux [3] and for a prediction of the development of extended air showers. Simulations predict that collisions of protons with a carbon target are very similar to proton interactions with air. This hypothesis could be directly tested with the HARP data. Measurements with cryogenic O_2 and N_2 targets [15], also shown in Fig. 1, confirm that p-C data can indeed be used to predict pion production in p- O_2 and p- N_2 interactions.

It is important to emphasize that a systematic campaign of measurements was performed by HARP: all thin target data taken with pion beams are analyzed and published now [16]. Similar results were also obtained for incoming protons [22]. Moreover, results on forward proton production in p-A and π^\pm -A interactions were published recently [23]. Fig. 2 shows the dependence on the atomic number A of the forward proton yields in p-A and π^\pm -A ($A = \text{Be, C, Al, Cu, Sn, Ta, Pb}$) interactions averaged over two forward angular regions ($0.05 \text{ rad} \leq \theta < 0.15 \text{ rad}$ and $0.15 \text{ rad} \leq \theta < 0.25 \text{ rad}$) and four momentum regions ($0.5 \text{ GeV}/c \leq p < 1.5 \text{ GeV}/c$, $1.5 \text{ GeV}/c \leq p < 2.5 \text{ GeV}/c$, $2.5 \text{ GeV}/c \leq p < 3.5 \text{ GeV}/c$ and $3.5 \text{ GeV}/c \leq p < 4.5 \text{ GeV}/c$), for the four different incoming beam momenta (3, 5, 8 and 12 GeV/c).

The advantage of all these measurements is that they were performed with the same detector, thus related systematic uncertainties are minimized.

1.2. Results obtained with the HARP large-angle spectrometer

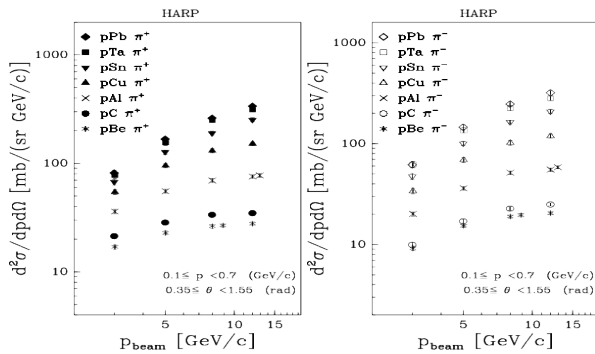


Figure 3: The dependence on the beam momentum of the π^+ (left) and π^- (right) production yields in p-A ($A = \text{Be, C, Al, Cu, Sn, Ta, Pb}$) interactions averaged over the forward angular region ($0.350 \text{ rad} \leq \theta < 1.550 \text{ rad}$) and momentum region $100 \text{ MeV}/c \leq p < 700 \text{ MeV}/c$. The results are given in arbitrary units, with a consistent scale between the left and right panel. Data points for different target nuclei and equal momenta are slightly shifted horizontally with respect to each other to increase the visibility.

First results on the measurements of the double-differential cross-section for the production of charged pions in p-A collisions emitted at large angles from the incoming beam direction were obtained for the full set of available nuclear targets using an initial part of the accelerator spill to avoid distortions in the TPC [17, 18, 19]. The pions were produced by proton beams in a momentum range from 3 GeV/c to 12 GeV/c hitting a target with a thickness of $5\% \lambda_I$. The angular and momentum range covered by the experiment ($100 \text{ MeV}/c \leq$

$p < 800 \text{ MeV}/c$ and $0.35 \text{ rad} \leq \theta < 2.15 \text{ rad}$) is of particular importance for the design of a neutrino factory. Track recognition, momentum determination and particle identification were all performed based on the measurements made with the TPC (see [17] for more details).

After the development of a special algorithm to correct for the TPC dynamic distortions [27] and validation of the TPC performance with benchmarks based on real data [28], full spill data were analyzed and published for incoming protons [20] and pions [21]. Fig. 3 illustrates the dependences of the measured charged pion yields on the beam momentum in p-A interactions averaged over the forward angular region ($0.350 \text{ rad} \leq \theta < 1.550 \text{ rad}$) and momentum region $100 \text{ MeV}/c \leq p < 700 \text{ MeV}/c$.

An additional comparison was also performed on the pion yields measured with the short ($5\% \lambda_I$) and long ($100\% \lambda_I$) nuclear targets [29].

All HARP measurements described above were compared with predictions of Monte-Carlo models available within GEANT4 [30] and MARS [31], as well as with the FLUKA [32] and GiBUU [33] models. Some models provide a reasonable description of HARP data in some regions (see e.g. [14, 15, 16, 17, 18, 19, 20, 21, 22, 23] and technical notes [34]), while there is no model which would describe all aspects of the data.

Tables with HARP results in text format are available from the DURHAM database [35].

2. The NA61/SHINE experiment

The physics program of the NA61 or SHINE (where SHINE \equiv SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS [36] consists of three main subjects. In the first stage of data taking measurements of hadron production in hadron-nucleus interactions needed for neutrino (T2K [37]) and cosmic-ray (Pierre Auger [38] and KASCADE [39]) experiments were performed. Later stages of the NA61 experiment study hadron production in proton-proton and proton-nucleus interactions with high statistics needed for a better understanding of high p_T production at SPS energies. Finally, the energy dependence of hadron production properties will be measured in p-p, p-Pb interactions as well as in nucleus-nucleus collisions, with the aim to identify the properties of the onset of deconfinement and find evidence for the critical point of strongly interacting matter.

The NA61/SHINE apparatus is a large acceptance spectrometer at the CERN SPS for the study of the hadronic final states produced in interactions of various beam particles (π , p, ions) with a variety of fixed

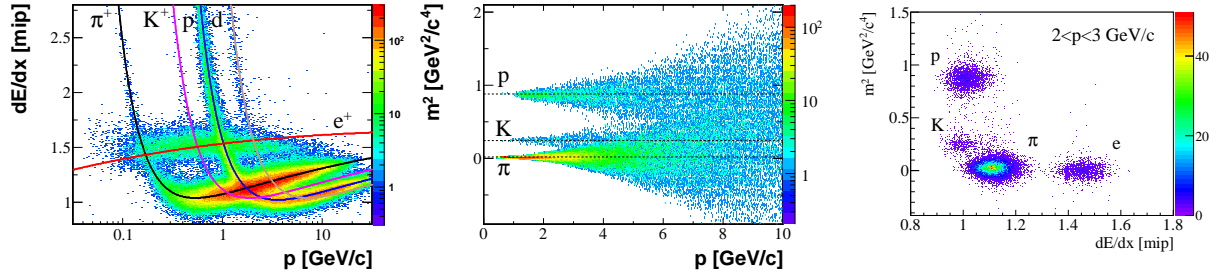


Figure 4: Examples of PID capabilities of the NA61/SHINE spectrometer for positively charged particles. (Left) Specific energy loss in the TPCs as a function of momentum. Curves show parameterizations of the mean dE/dx calculated for different particle species. (Middle) Mass squared, derived from the ToF-F measurement and the fitted path length and momentum, versus momentum. The lines show the expected mass squared values for different particles. (Right) Example of two-dimensional m^2 – dE/dx plot for the momentum range 2–3 GeV/c. Four clear accumulations corresponding to positrons, pions, kaons and protons are observed. The combination of both m^2 and dE/dx measurements provides close to 100% purity in the pion selection over the whole momentum range.

targets at the SPS energies. The main components of the current detector were constructed and used by the NA49 experiment [40]. The main tracking devices are four large volume TPCs. Two of them, the vertex TPCs (VTPC-1 and VTPC-2), are located in the magnetic field of two super-conducting dipole magnets (maximum bending power of 9 Tm) and two others (MTPC-L and MTPC-R) are positioned downstream of the magnets symmetrically with respect to the beam line. One additional small TPC, the so-called gap TPC (GTPC), is installed on the beam axis between the vertex TPCs. The setup is supplemented by time of flight detector arrays two of which (ToF-L/R) were inherited from NA49 and can provide a time measurement resolution of $\sigma_{tof} \leq 90$ ps. A new forward time of flight detector (ToF-F) with a time resolution of ~ 120 ps was constructed in order to extend the acceptance of the NA61/SHINE setup for pion and kaon identification as required for the T2K measurements. The particle identification in NA61 is based on the differential energy loss dE/dx measured in the TPCs combined with the mass squared measurements based on the ToF information, see Fig. 4.

Two carbon (isotropic graphite) targets were used for T2K-related measurements: 1) a 2 cm-long target (about 4% λ_I) with density $\rho = 1.84$ g/cm³, the so-called thin target; 2) a 90 cm long cylinder of 2.6 cm diameter (about 1.9 λ_I), the so-called T2K replica target with density $\rho = 1.83$ g/cm³.

2.1. First thin-target results

The NA61/SHINE experiment was approved at CERN in June 2007. The first pilot run was performed during October 2007. In total about 670 k events with the thin target, 230 k events with the T2K replica tar-

get and 80 k events without target (empty target events) were registered during the 2007 run. Using these data interaction cross sections and charged pion spectra in p-C interactions at 31 GeV/c were first measured [41]. Such measurements are required to improve predictions of the neutrino flux for the T2K long baseline neutrino oscillation experiment in Japan [37].

For normalization and cross section measurements we adopted the same procedure as the one developed by the NA49 Collaboration [43]. The measured inelastic and production cross sections in p-C interactions at 31 GeV/c [44] are $257.2 \pm 1.9 \pm 8.9$ mb and $229.3 \pm 1.9 \pm 9.0$ mb, respectively.

Crucial for this analysis is the identification of the produced charged pions. Depending on the momentum interval, different approaches have been adopted, which lead also to different track selection criteria. The task is facilitated for the negatively charged pions, by the observation that more than 90% of primary negatively charged particles produced in p-C interactions at this energy are π^- , and thus the analysis of π^- spectra can also be carried out without additional particle identification.

Three analysis methods were developed to obtain charged pion spectra. These are: 1) analysis of π^- mesons via measurements of negatively charged particles (*h⁻ analysis*); 2) analysis of π^+ and π^- mesons identified via dE/dx measurements in the TPCs (*dE/dx analysis at low momentum*) and 3) analysis of π^+ and π^- mesons identified via time-of-flight and dE/dx measurements in the ToF-F and TPCs, respectively (*tof – dE/dx analysis*). Each analysis yields fully corrected pion spectra with independently calculated statistical and systematic errors. The spectra were compared in overlapping phase-space domains to check their consistency. Complementary domains were combined to

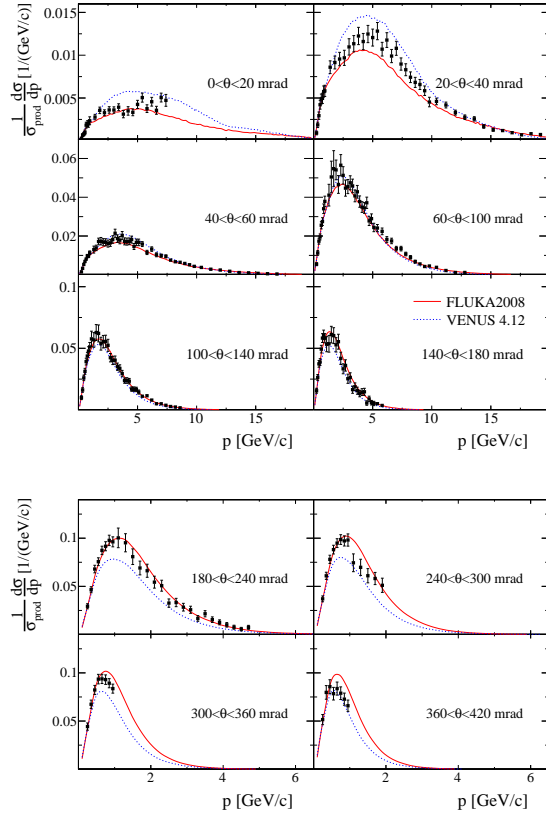


Figure 5: Laboratory momentum distributions of π^+ mesons produced in production p-C interactions at 31 GeV/c in different intervals of polar angle (θ). The spectra are normalized to the mean π^+ multiplicity in all production p-C interactions. Error bars indicate statistical and systematic uncertainties added in quadrature. The overall uncertainty (2.3%) due to the normalization procedure is not shown. Predictions of hadron production models, FLUKA2008 (solid line) and VENUS4.12 (dotted line) are also indicated.

reach maximum acceptance.

The agreement between spectra obtained by different methods is, in general, better than 10%. In order to obtain the final spectra consisting of statistically uncorrelated points the measurement with the smallest total error was selected.

Inclusive production cross sections for negatively and positively charged pions are presented as a function of laboratory momentum in 10 intervals of the laboratory polar angle covering the range from 0 up to 420 mrad [41]. The final spectra for π^+ are plotted in Fig. 5. For the purpose of a comparison of the data with model predictions the spectra were normalized to the mean π^+ multiplicity in all production interactions. This avoids uncertainties due to the different treatment of quasi-elastic interactions in models as well as problems

due to the absence of predictions for inclusive cross sections. A clear advantage of NA61/SHINE is that it fully covers the kinematic phase-space of interest for T2K.

It is interesting to compare the π^+ spectra in p-C interactions at 31 GeV/c to the predictions of event generators of hadronic interactions. Models that have been frequently used for the interpretation of cosmic ray data, i.e. VENUS4.12 [48], FLUKA2008 [32] and URQMD1.3.1 [49] were selected. They are part of the CORSIKA [50] framework for the simulation of air showers and are typically used to generate hadron-air interactions at energies below 80 GeV. In order to ensure that all relevant settings of the generators are identical to the ones used in air shower simulations, p-C interactions at 31 GeV/c were simulated within CORSIKA in the so-called *interaction test* mode. The results are presented in Fig. 5. More model comparisons can be found in the technical notes [51].

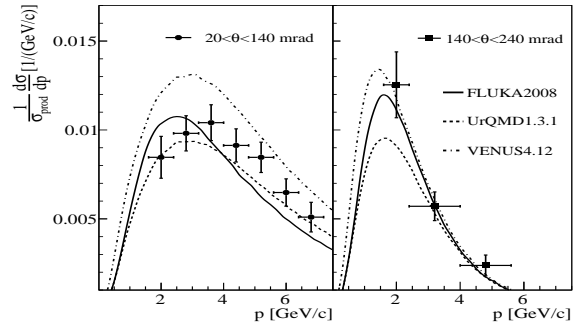


Figure 6: Comparison of measured K^+ spectra with model predictions. Distributions are normalized to the mean K^+ multiplicity in all production p+C interactions. The vertical error bars on the data points show the total (stat. and syst.) uncertainty. The horizontal error bars indicate the bin size in momentum.

Recently, the *tof* – *dE/dx* analysis was applied to the same set of 2007 data in order to perform measurements of differential production cross sections of positively charged kaons in p+C interactions at 31 GeV/c [42]. The corresponding results are shown in Fig. 6 together with model predictions. The knowledge of kaon production is crucial for precisely predicting the intrinsic electron neutrino component and the high energy tail of the T2K beam.

Moreover, preliminary results for protons were also obtained [45, 46], see Fig. 7. The analysis of neutral strange particle production using V^0 -like topology of their decays is currently ongoing. First preliminary results can be found in [47].

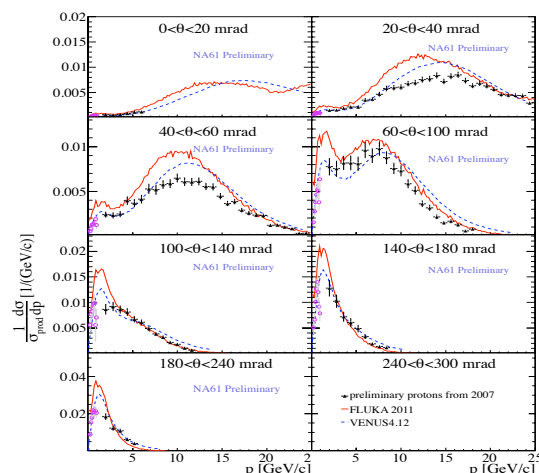


Figure 7: Laboratory momentum distributions of protons produced in p-C interactions at 31 GeV/c in different intervals of polar angle (θ). The spectra are normalized to the mean proton multiplicity in all production p-C interactions. Error bars indicate statistical and systematic uncertainties added in quadrature. The overall uncertainty (2.3%) due to the normalization procedure is not shown. Predictions of hadron production models, FLUKA2011 (solid line) and VENUS4.12 (dashed line) are also indicated.

2.2. First replica-target results

First measurements of pion emission from the T2K replica target were also performed [52].

The main motivation for measurements of hadron emission from a replica of the T2K target is to reduce the systematic uncertainties on the prediction of the initial neutrino flux originating from re-interactions in the long target.

The long-target analysis presented here uses the low-statistics data collected in 2007 [53]. It however sets the ground for the ongoing analysis of high-statistics NA61/SHINE data with the replica of the T2K target. It demonstrates that high-quality long-target data were successfully taken with the NA61/SHINE apparatus for T2K, and that such data can effectively be used to constrain the T2K neutrino flux predictions. A comparison of neutrino flux predictions based on thin-target hadron production measurements and long-target hadron emission measurements was performed as an illustration of the complete procedure, see Fig. 8. A very good agreement between these two complementary approaches is observed. It is important to stress that this is the first complete example of application of long-target data for neutrino flux predictions.

The data presented here and in Refs. [41, 42, 53] already provide important information used for improved

calculation of the T2K neutrino flux. Meanwhile, a much larger data set with both the thin (4% λ_1) and the T2K replica carbon targets was recorded in 2009 (about 6 M triggers with the thin target and 2 M triggers with the replica target) and 2010 (about 10 M triggers with the replica target) and is presently being analyzed. This will lead to results of higher precision for charged pions and kaons, protons, K_S^0 and Λ . The new data will allow a further significant reduction of the uncertainties in the prediction of the neutrino flux in the T2K experiment.

3. Conclusions

The HARP experiment has already made important contributions to the cross-section measurements relevant for neutrino experiments.

First measurements of charged pion and kaon production in p-C interactions at 31 GeV/c released recently by NA61/SHINE are of significant importance and were already employed for precise predictions of the J-PARC neutrino beam used for the first stage of the T2K experiment.

Both experiments provide also a large amount of input for validation and tuning of hadron production models in Monte-Carlo generators.

Thus, hadron production experiments have already contributed to the recent advances in neutrino physics. Clearly, hadroproduction studies are a *must* for future precision neutrino experiments.

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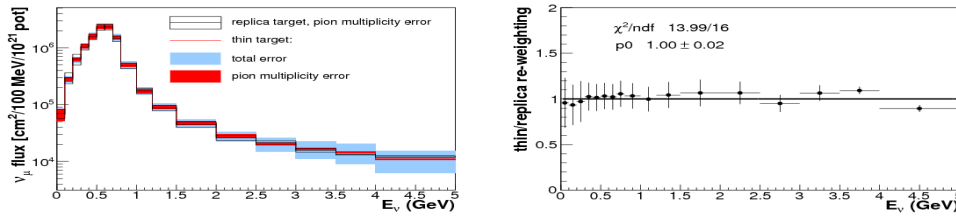


Figure 8: Re-weighted ν_μ flux predictions at the far detector of T2K based on the NA61 thin-target and replica-target data [left] and ratio of the two predictions [right]. A linear fit to the ratio is shown by the solid line.

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